BEYOND THE STANDARD MODEL
PHYSICS SEARCHES AT THE TEVATRON [*]

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The recent results on a number of searches performed at Tevatron for new phenomena beyond Standard Model are presented. The topics include the experimental tests of SUSY with mSUGRA and GMSB breaking scenarios. The latest analyses on large extra dimensions, new massive bosons are covered as well. The results are based on experimental data samples collected at the Tevatron with CDF and DØ detectors and comprising a total integrated luminosity up to $\sim 2.7\,\mathrm{fb}^{-1}$.

1 Experimental Apparatus

CDF and DØ Collaborations are running experiments at the Tevatron collider collecting data from $p\overline{p}$ collisions at an energy of $\sqrt{s} = 1960\,\mathrm{GeV}$. The CDF II (later CDF) and DØ are upgraded multipurpose high-energy physics detectors [1] with silicon vertex detectors, central tracking, electromagnetic and hadron calorimetry and muon identification systems. To the date of this presentation the Tevatron machine delivered more than $4\,\mathrm{fb}^{-1}$ integrated luminosity. The analyses to be discussed below are based on an amount of data corresponding to integrated luminosity $\int \mathcal{L}\, dt$ up to $\sim 2.7\,\mathrm{fb}^{-1}$.

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2   SUSY Searches at the Tevatron

Supersymmetry (SUSY) transforms fermions into bosons and vice versa. The SUSY theoretical approach offers solutions for several theoretical and experimental challenges of modern high-energy physics. It resolves the divergences inherent to a Standard Model ("hierarchy problem") and provides candidates for Dark Matter. It creates harmony with unification theories at the Planck scale and embodies gravity opening a path to a string theory. Since superpartners of known Standard Model (SM) particles have not yet been observed, SUSY is a broken symmetry. In our searches we consider a Minimal SUSY Model (MSSM) within its two breaking scenarios, mSUGRA and GMSB, as the benchmarks for the theoretical predictions. mSUGRA is broken by gravity at the Planck scale. With R-parity invariance [2], the mSUGRA spectrum and its interaction strengths are determined by 5 parameters: soft breaking scalar and fermion scales $m_0, m_{1/2}$, trilinear coupling A_0, ratio $\tan\beta = \langle H_u \rangle / \langle H_d \rangle$, and sign of the trilinear coupling in a Higgsino mass term $sgn(\mu_0)$. The lightest SUSY particle (LSP) in mSUGRA is the neutralino ($\widetilde{\chi}_1^0$). In the MSSM with gauge-mediated supersymmetry-breaking (GMSB) scenario, the breaking is communicated via gauge fields (e.g. EWK or QCD) and at a much lower scale of $\Lambda \sim 100\,\text{TeV}$. The minimal GMSB scenario is again R-parity invariant and is determined by Λ, mass of a messenger field M_{mess}, number of messenger fields N_5, $\tan\beta$ and $sgn(\mu_0)$. The LSP in GMSB framework is the gravitino ($\widetilde{G}$) and the next-to-LSP (NLSP) is the neutralino $\widetilde{\chi}_1^0$. For further details please see some nice introductions to the subject in [3].

One of the promising production modes of SUSY is the pairs of the lightest chargino $\widetilde{\chi}_1^\pm$ and next-to-lightest neutralino $\widetilde{\chi}_2^0$ decaying into three leptons and neutrinos with the LSP $\widetilde{\chi}_1^0$ unobservable. The CDF analysis [4] is based on $\sim 2.0\,\text{fb}^{-1}$ of integrated luminosity. The DØ Collaboration [5] performed the trilepton searches with two samples of $590\,\text{pb}^{-1}$ and of $1.0\,\text{fb}^{-1}$ and combined the two results. Both experiments looked for modes in two categories – channels with three leptons and channels with two leptons and a single isolated track measured by a tracking system. The leptons are μ identified by muon chambers or e identified as an electromagnetic cluster matched with a track. Both analyses required large $\not{E}_T \gtrsim 20\,\text{GeV}$, high-$p_T$ leptons, applied anti-Z^0, anti-$t\bar{t}$, anti-W cuts, and suppressed jet activity. Both experiments found in the selected signal regions good agreement between the number of observed events and the event count predicted by the SM. The upper limits were set on the production cross-sections in the mSUGRA framework. Please see Fig. 1.
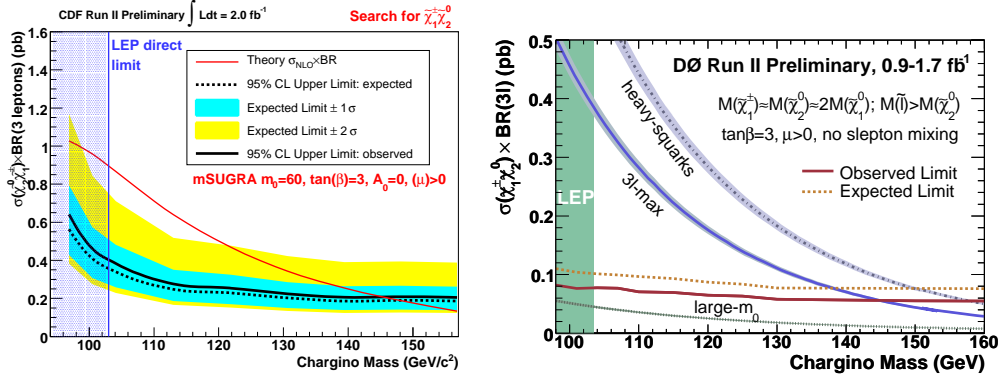
Figure 1: The search for chargino-neutralino production. CDF [4] shows expected and observed limits for mSUGRA with $m_0 = 60 \, \mathrm{GeV}/c^2$. CDF sets the lower limit for $m(\widetilde{\chi}_1^\pm) > 145 \, \mathrm{GeV}/c^2$ at 95% C.L. DØ [5] uses several mSUGRA scenarios and for the $3l$-max scenario $m(\widetilde{\chi}_1^\pm) > 140 \, \mathrm{GeV}/c^2$ at 95% C.L. Please note the difference in mSUGRA benchmarks used by CDF and DØ experiments.

The $p\overline{p}$ collisions at $\sqrt{s} = 1960 \, \mathrm{GeV}$ created by the Tevatron is a good place to search for the production of squarks ($\widetilde{q}$) and gluinos ($\widetilde{g}$) in both CDF and DØ detectors. The optimism comes from the fact that the rates of $\widetilde{q}$ and $\widetilde{g}$ are enhanced by a strong interaction α_S involved in the processes. Depending on the mass relation between $\widetilde{q}$ and $\widetilde{g}$ ($M(\widetilde{q}) \lesssim | \gtrsim | \simeq M(\widetilde{g})$) and availability of phase space to produce pairs of ($\widetilde{q},\widetilde{q}$), ($\widetilde{g},\widetilde{g}$) or ($\widetilde{q},\widetilde{g}$), their decays cascade to ≥ 2-, ≥ 4- or ≥ 3- jet topologies with a large $\not{E}_T$ caused by neutralinos $\widetilde{\chi}_1^0$ leaving no signals in the detectors. CDF analyzed [6] all three possible topologies using $\int \mathcal{L} \, dt = 2 \, \mathrm{fb}^{-1}$ of collected data. The cuts to individual jet E_T^{jet} optimized for every topology, to missing $\not{E}_T$ and total H_T ($\equiv \sum E_T^{jet}$) have been applied together with lepton vetoes to suppress a SM contribution coming from W / Z^0, $t\overline{t}$ and QCD multi-jet events. The observed event count was found to be consistent with the SM background estimates and the exclusion limits at 95% C.L. were set in the $M(\widetilde{q})$ vs $M(\widetilde{g})$ plane as shown in Fig. 2 together with a published analogous analysis from DØ [7].

Within MSSM framework the SUSY partners of the t-quark, scalar tops, are strongly mixed [3] resulting in a significant splitting between eigenstates, $M(\widetilde{t}_1) < M(\widetilde{t}_2)$. Moreover the $\widetilde{t}_1$ could be the lightest $\widetilde{q}$ and even $M(\widetilde{t}_1) \lesssim m(t)$. Based on data of $\int \mathcal{L} \, dt =$
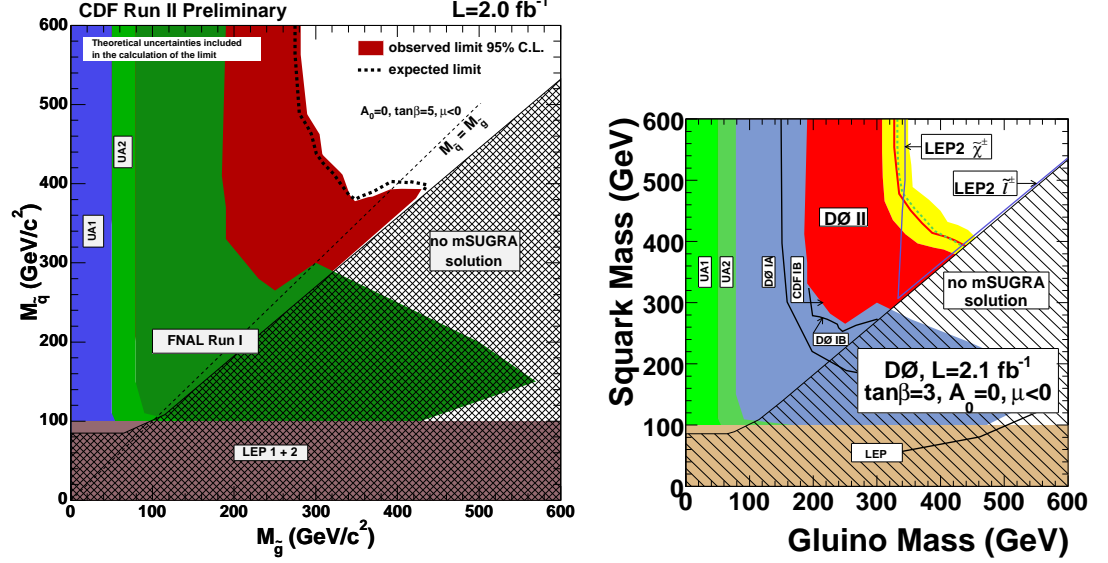
Figure 2: CDF and DØ results: the observed (red) and expected (dashed line) exclusion limits at the 95% C.L. CDF uses mSUGRA with $\tan\beta = 5$, $A_0 = 0$, $\mu_0 < 0$ and sets lower limits [6] $M > 392\,\mathrm{GeV}/c^2$ @95% C.L. for $M(\widetilde{g}) \simeq M(\widetilde{q})$, $M(\widetilde{g}) > 280\,\mathrm{GeV}/c^2$ @95% C.L. for every $M(\widetilde{q})$ and $M(\widetilde{g}) > 423\,\mathrm{GeV}/c^2$ @95% C.L. for $M(\widetilde{q}) < 378\,\mathrm{GeV}/c^2$. DØ uses mSUGRA with $\tan\beta = 3$, $A_0 = 0$, $\mu_0 < 0$ and sets lower limits [7] $M(\widetilde{q}) > 379\,\mathrm{GeV}/c^2$, $M(\widetilde{g}) > 308\,\mathrm{GeV}/c^2$ @95% C.L.

$2.7\,\mathrm{fb}^{-1}$, CDF performed a search for the scalar top [8]. The 2-body decay $\widetilde{t}_1 \to b\widetilde{\chi}_1^\pm$, is assumed to be dominant with $\mathcal{B} = 100\%$, while $\widetilde{\chi}_1^\pm \to \widetilde{\chi}_1^0 l\nu_\ell$ via a variety of modes. The assumption is valid provided $\widetilde{\chi}_1^0$ is LSP (mSUGRA), $M(\widetilde{t}_1) \lesssim m(t)$ and $M(\widetilde{\chi}_1^\pm) < M(\widetilde{t}_1) - m(b)$. Then $M(\widetilde{t}_1)$ is reconstructed kinematically in the assumed decay mode and the mass itself is used as a variable to discriminate stop from the SM background. The experimental signature of produced pairs $\widetilde{t}_1\overline{\widetilde{t}_1}$ is $l^+l^- + jet_1 jet_2 + \not{E}_T$. Two data samples, b-tagged and anti-tagged, are considered with slightly different analysis cuts. Finally, the limits on the dilepton branching ratio at $\sigma_{theor}(\widetilde{t}_1\overline{\widetilde{t}_1})$ for the 3-d mass area of $M(\widetilde{t}_1) \in (115, 185)$, $M(\widetilde{\chi}_1^0) \in (43.9, 88.5)$ and $M(\widetilde{\chi}_1^\pm) \in (105.8, 125.8)$ are set. Please see Fig. 3. DØ Collaboration performed a similar analysis [9] based on $1.1\,\mathrm{fb}^{-1}$. The $\widetilde{t}_1$

mode was assumed to be the same as CDF, but the LSP in the SUSY benchmark was conjectured to be sneutrino ($\widetilde{\nu}$).
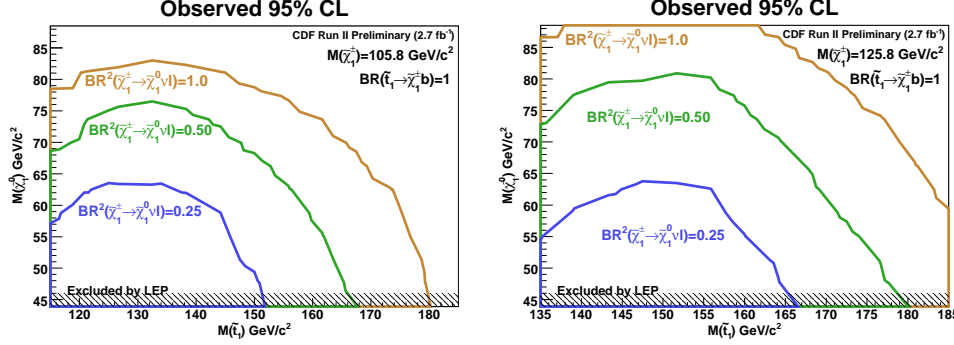

Figure 3: CDF preliminary results on the scalar top [8]. $M(\widetilde{\chi}_1^0)$ vs $M(\widetilde{t}_1)$ plane with regions excluded at 95% C.L., for various dilepton branching ratios, at $M(\widetilde{\chi}_1^\pm) = 105.8\,\text{GeV}$ (left) and at $M(\widetilde{\chi}_1^\pm) = 125.8\,\text{GeV}$ (right). The electrons, muons and taus are all assumed to equally contribute to the dilepton final state.

An interesting decay mode gets opened once we allow for the stop quark to decay as $\widetilde{t}_1 \to \widetilde{\chi}_1^0$ via FCNC penguin diagram. DØ Collaboration searched [10] for this mode assuming its $\mathcal{B} = 100\%$ and analyzing the events with two charm acoplanar jets and $\not{E}_T$ using a dataset of $\int \mathcal{L}\,dt = 1.0\,\text{fb}^{-1}$. With the theoretical uncertainty on the $\sigma_{theor}(\widetilde{t}_1\overline{\widetilde{t}_1})$ propagated properly, the largest limit was set for $M(\widetilde{t}_1) > 150\,\text{GeV}$ at 95% C.L. for LSP mass set to $M(\widetilde{\chi}_1^0) = 65\,\text{GeV}$.

The scalar bottom eigenstates predicted by MSSM are noticeably split given a strong mixing due to a large $\tan\beta > 10$ and large negative contribution of corresponding top Yukawa coupling [3]. Consequently the lightest sbottom eigenstate $\widetilde{b}_1$ can be reached at Tevatron energies. CDF used $\int \mathcal{L}\,dt = 2.5\,\text{fb}^{-1}$ of data collected by an inclusive $\not{E}_T$ trigger to search [11] for the $\widetilde{b}_1$ states *in decays of gluinos* ($\widetilde{g}$) expected to be abundantly produced at Tevatron, $p\overline{p} \to \widetilde{g}\widetilde{g} \to \widetilde{b}_1\overline{\widetilde{b}_1}$. The $M(\widetilde{g}) > M(\widetilde{b}_1)$ and further mass relations of $M(\widetilde{t}_1), M(\widetilde{\chi}_1^\pm) > M(\widetilde{b}_1) > M(\widetilde{\chi}_1^0)$ allow for the decay mode with $\mathcal{B}(\widetilde{g} \to b\widetilde{b}_1, \widetilde{b}_1 \to b\widetilde{\chi}_1^0) = 100\%$ to be dominant. This area of phase space was probed by the data analysis. The experimental signature of the pair $\widetilde{b}_1\overline{\widetilde{b}_1}$ is 4b-jets+$\not{E}_T$ and CDF required at least 2 b-jets to be b-tags. No significant deviation from the SM was observed and the exclusion limits were set using only the 2 b-tags sample. Please see Fig. 4.
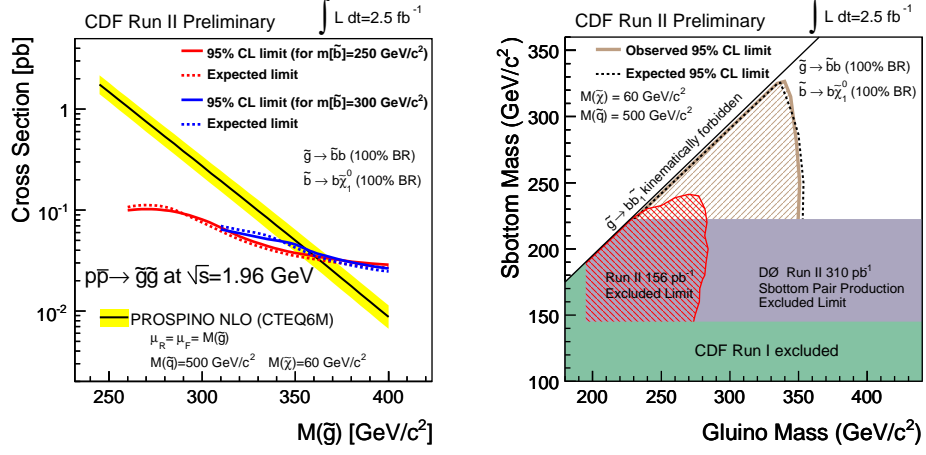
Figure 4: Left: Upper limit on $\sigma(p\overline{p} \to \widetilde{g}\widetilde{g}, \, \widetilde{g} \to b\widetilde{b}_1 \, (100\%))$ at 95% C.L. as a function of $M(\widetilde{g})$ for two different $M(\widetilde{b}_1) = 250, 300 \, \mathrm{GeV}/c^2$. Right: $M(\widetilde{b}_1)$ vs $M(\widetilde{g})$ exclusion plot showing observed and expected limits at 95% C.L. with R-parity conserved. Please see the details in [11].

The analyses presented above used an mSUGRA as a benchmark to set exclusion areas on mass plots or limits on cross-sections. DØ Collaboration has undertaken a search [12] for signatures of MSSM with GMSB breaking scenario. LSP in GMSB is the gravitino $\widetilde{G}$. A neutralino (NLSP) having admixture of photino decays predominantly in the mode $\widetilde{\chi}_1^0 \to \gamma\widetilde{G}$. Hence, assuming R_P invariance, the GMSB event should have a signature of $\gamma\gamma + \not{E}_T$ in a final state. DØ Collaboration has analyzed $\int \mathcal{L} \, dt = 1.1 \, \mathrm{fb}^{-1}$ of data. Two photons above 25 GeV have been selected and an excess of events over SM backgrounds was searched in $\not{E}_T > 60 \, \mathrm{GeV}$ range. Please see the left plot at Fig. 5. No significant excess of the event count in $\not{E}_T$ spectrum over expected SM background was found. The most stringent lower limits on the GMSB signal cross section to date were set for gaugino masses $M(\widetilde{\chi}_1^0) \gtrsim 125 \, \mathrm{GeV}$ and $M(\widetilde{\chi}_1^{\pm}) \gtrsim 229 \, \mathrm{GeV}$. See the right plot at Fig. 5.
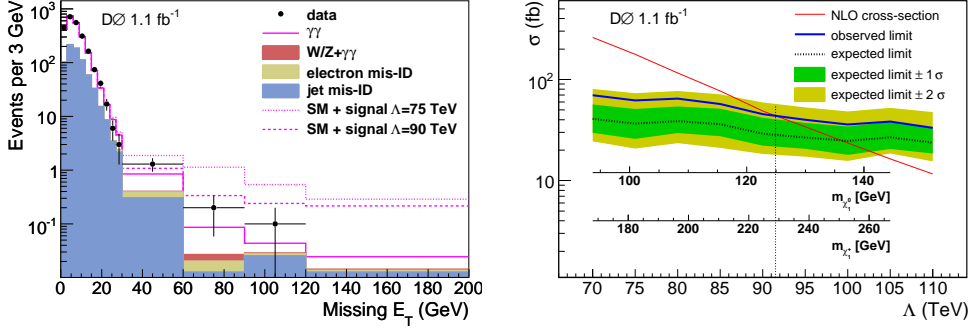
Figure 5: Left: The $\not{E}_T$ distribution in $\gamma\gamma$ data together with various SM background contributions. The dotted-dashed line shows the GMSB SUSY theoretical prediction. Right: The predicted cross section for the Snowmass Slope model versus Λ (see [12] and references therein). The observed (solid line) and expected (dash-dotted) upper limits at 95% C.L. are shown. Please see the details in [12].

3 Non-SUSY Searches at the Tevatron

One of the exciting topics among non-SUSY searches is the one concerned with Large Extra Dimensions (or LED). A theory of LED has been outlined by the authors [13]. From an experimental point of view the basic subprocesses where we could expect the LED to reveal itself are the mono-photons in $q\widetilde{q} \to \gamma\, G_{KK}$ or mono-jets in $qg \to q\, G_{KK}$, $gg \to g\, G_{KK}$ always associated with large $\not{E}_T$. DØ searched for events with $\gamma + \not{E}_T$ in a final state [14] using the data of $\int \mathcal{L}\, dt = 2.7\,\mathrm{fb}^{-1}$ collected with a trigger on electromagnetic clusters of $E_T(\gamma) > 20\,\mathrm{GeV}$. The analyzed photon sample consisted of events with only a single photon having transverse momentum $p_T(\gamma) > 90\,\mathrm{GeV}$ and with $\not{E}_T > 70\,\mathrm{GeV}$. The CDF Collaboration in a similar analysis [15] based on $2.0\,\mathrm{fb}^{-1}$ combined both single γ and mono-jet results and set the limits. The results of both analyses are summarized in Table 1.

Exotic models like GUT E_6 extension of Standard Model or quantum gravitational Randall-Sundrum model predict high mass resonances in di-lepton modes $Z'^0 \to l^+l^-$ [16]. Using a total luminosity $\int \mathcal{L}\, dt = 2.5\,\mathrm{fb}^{-1}$, CDF searched for dielectron resonance candidates of $Z'^0 \to e^+e^-$ [17]. Given that the search probes the mass range $M(e^+e^-) \in (150, 1000)\,\mathrm{GeV}/c^2$ an excess of $\sim 3.8\sigma$ was found in the $M(e^+e^-) \sim 240\,\mathrm{GeV}/c^2$ region

Analysis:	DØ, $\gamma + \not{E}_T$, $2.7\,\mathrm{fb}^{-1}$		CDF Prelim., Jet/$\gamma + \not{E}_T$, $2.0\,\mathrm{fb}^{-1}$	
$\mathbf{N_{LED}}$	$\sigma^{95}_{obs(exp)}$	$M_D^{obs(exp)}$	$\sigma^{95}_{obs(exp)}$	$M_D^{obs(exp)}$
2	19.0 (14.6)	970 (1037)	26.3	1420
3	20.1 (14.7)	899 (957)	38.7	1160
4	20.1 (14.9)	867 (916)	46.9	1060
5	19.9 (15.0)	848 (883)	52.7	990
6	18.2 (15.2)	831 (850)	56.7	950
7	15.9 (14.9)	834 (841)		
8	17.3 (15.0)	804 (816)		

Table 1: The upper limit at 95% C.L. set for a cross-section by DØ [14] and CDF [15] and the 95% C.L. lower limit set for a fundamental Planck scale M_D are shown in the table.

with $\alpha = 0.6\%$ caused by the background fluctuation. The lower mass limit on SM coupling Z'^0, $M(Z'^0_{SM}) > 966\,\mathrm{GeV}/c^2$ was set at 95% C.L. The RS graviton with a mass below $850\,\mathrm{GeV}/c^2$ was excluded at 95% C.L. assuming $k/\overline{M}_{Planck} = 0.1$.

Acknowledgements

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